The "Weak Spots" in Stacked UHF RFID Tags in NFC Applications

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Abstract— **In near-field (NF) applications, stacked UHF RFID tags are known to be less readable than the stand-alone tags. It is also intuitively known that "weak spots" exist when more tags are stacked together, especially when the tags are placed closer to each other. However, "weak spots" in NF-RFID had not been theoretically analyzed in the past, nor had the phenomena been quantitatively measured. In this paper, we show that the "weak spots" are mainly the results of mutual coupling between the tag antennas in NF, we also demonstrate that the profiles of the weak spots are strongly determined by the separation between tags, and they are not monotonically distributed along the stack, i.e., weakest spots are not necessarily on the far end or the center of the stack. To verify our analysis, EM tool simulation and lab measurements are conducted, the results from theoretical calculation, simulation and experiments agree with each other nicely.**

Keywords- NF RFID antenna, stacked RFID tags,; inductive coupling; weak spots;

I. Introduction

As UHF RFID technology matured in recent years, near-field-communication (NFC) applications are no longer the domain dominated by HF (high frequency) tags; UHF tags had demonstrated the advantages of lower materials cost, superior anti-collision algorithms and a unified paradigm for both NF and FF (far-field) RFID infrastructures [1-3]. The item-level deployments powered by UHF tags are in a steady growth in libraries, pharmaceutical medicines and jewelry package applications [4-7]. It is widely expected that UHF RFID tags will eventually dominate the NF application market in the next decades.

Unlike RFID used in far-field applications, where tags respond to readers through backscattering, in near-field applications, tags and readers communicate to each other through inductive coupling [8-14]. The reader transmits signals through the near-field antenna that generates inductive field. The tag antenna, being inside the field; generates a coupling current that both powers up the tag's circuitry and carries the reader signals. Upon responding to the reader, the tag will modulate the current inside the antenna loop. The modulated current will again couple with the reader antenna and subsequently be detected by the reader receiver.

However, the coupled current in one tag's antenna loop will also create an inductive field that couples with other tags' antennas. This field may interfere with the coupling field from the reader. While there are many tags in the reader's inductive field (near field), the mutual coupling between the tags may create interference current in each other's antenna loop, especially when the tags are stacked vertically with small separation, as shown in Fig. 1. Some tags may receive more interference than others, thus "weak spots"; sometime the "dead spots" are formed.

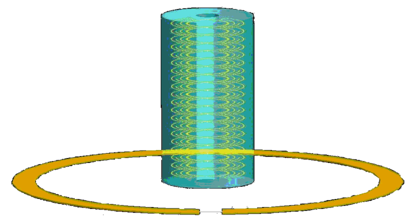

Figure 1. Tag and reader antennas coupling in NF inductive field

Mutual interference between tags will be more significant when the tags are packed closer to each other. Field experiments also demonstrate that weak spots occur more often in stacks with more tags, or stacks that are densely packed. However, more detailed measurement of the weak spots may turn out to be not so "intuitive": when the tags are stacked closer enough, the weak spots may not be the tags located at the far-end of the stack, nor in the center of the stack. The profile of the weak spots will depend on the spacing between the tags, and they may not present a simple monotonic distribution as well.

This paper will present a theoretical analysis of the mutual coupling effects between the stacked RFID tags in near-field. A mutual coupling model is formulated to quantify the interference effect on each of the tag antennas along the stack. Using this model, weak spot profiles of the stack can be calculated and illustrated. We also perform the mutual coupling analysis by using an EM simulation tool called AMDS (antenna modeling design system) from Agilent. We construct 20 NF tag models in the simulation environment, each with a ring antenna and tags are stacked vertically with different separation. The simulation results agree well with our theoretical analysis and show the same profile of weak spot distribution.

Field tests are also conducted to verify the results from both theoretical and simulation analysis. 20 NF tag are stacked with the same setting used in EM simulation and calculation. The activation power of each tag on the stack is measured and the difference of activation power level demonstrates a profile of the weak spots. These measurements also align nicely with results from calculation and simulation.

The paper is organized as follows; Section 2 presents mutual coupling models for reader-tag and tag-tag interaction. Using this model, weak spots profiles are calculated in section 3. EM tool simulation results are introduced in Section 4, while lab experiments are performed in Section 5. Conclusion is summarized in Section 6.

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II. COUPLING OF NEAR-FIELD ANTENNAS

A. Reader-Tag Inductive Coupling Model

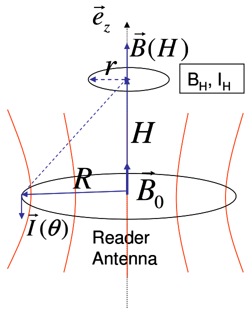

Figure 2. Tag and reader antenna coupling in NF inductive field

In near-field applications, RFID reader and tag antennas use inductive coupling to interact [15-16]. Without loss of generality, reader and tag antennas can be modeled as two circular loops, as shown in Fig. 2. The magnetic flux density along the center axis perpendicular to the reader antenna loop plane is given by.

$$\vec{B}(H) = \frac{\mu_0}{4\pi}\int_0^{2\pi} \frac{\vec{I}(\theta)\times(\vec{H}-\vec{R})}{\left|\vec{H}-\vec{R}\right|^3} R\cdot d\theta \tag{1}$$

Where $\vec{I}(\theta)$ is the current inside the reader antenna and it varies over time and the angular position θ around the loop. $\vec{H}$ is the positional vector from the reader antenna loop center to the tag antenna loop center. $\vec{R}$ is the radius vector along the angle θ and $(\vec{H}-\vec{R})$ represents the positional vector starting from the current segment on the reader antenna loop pointing to the center of tag loop above the reader antenna plane. By integrating the magnetic density generated by each current segment along the reader loop, the total magnetic flux density induced from the reader, at position $\vec{H}$, can be calculated.

The scalar value of $\vec{B}(H)$ along Z axis, $B(H)_z$, can be further expressed as

$$B(H)_z = \left(\frac{R^2}{R^2+H^2}\right)^{3/2} \cdot \frac{\mu_0 \int_0^{2\pi} I(\theta)d\theta}{4\pi R} \tag{2}$$

Where H and R are the scalar value of $\vec{H}$ and $\vec{R}$ respectively.

Because $B(H)_z$ is the magnetic flux density contributed from all segments along the reader loop, we can further simplify the integration as

$$B(H)_z = \left(\frac{R^2}{R^2+H^2}\right)^{3/2} \cdot \frac{\mu_0 I_{ave}}{2R} \tag{3}$$

Where $I_{ave} = \int_0^{2\pi} I(\theta)d\theta \Big/ 2\pi$ represents the average current inside the loop.

Here we define the reader-tag mutual inductance M_H as the total magnetic flux in the tag antenna loop divided by the driving current from the reader, i.e., I_{ave}. We assume the tag is put along the center axis above the reader antenna where the magnetic flux density is close to uniform around the tag antenna area. The magnetic flux can be estimated as $B_H \cdot A_{loop}$ and the mutual inductance is

$$M_H = \frac{B_H \cdot A_{loop}}{I_{ave}} = \left(\frac{R^2}{R^2+H^2}\right)^{3/2} \cdot \frac{\mu_0 A_{loop}}{2R} \tag{4}$$

where A_{loop} is the area covered by tag antenna loop.

B. Coupling Current inside the Tag Antenna Loop

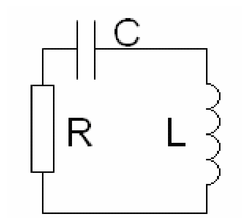

Figure 3. Equivalent Circuit of a Tag

The tag can be modeled as a simple RCL equivalent circuit and the coupling current inside the tag antenna loop can be calculated as

$$I_H = \frac{-j\omega M_H I_{ave}}{R_{chip} + 1/j\omega C + j\omega L} \tag{5}$$

The negative sign in the equation denotes that the coupling current is always on the opposite direction of the driving current, in this case, the I_{ave} inside the reader antenna.

C. Coupling Between Two Tags

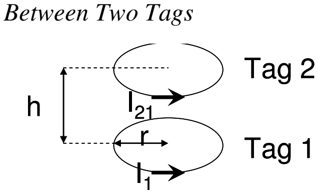

Figure 4. Coupling between two tag antennas in NF

Similar to the reader-tag coupling model above, the mutual coupling between two adjacent tag antenna loops can be analyzed in the following way.

Assuming two identical tag antenna loops 1 and 2, of radius r, are placed vertically with a separation of h_{21}. Similar to the analysis in Eq. 3, the magnetic flux density generated by antenna 1 along the vertical axis above its antenna plane can be expressed as

$$B_{21} = (\frac{r^2}{r^2 + h_{21}^2})^{3/2} \cdot \frac{\mu_0 I_1}{2r} \quad (6)$$

Where I_1 is the current inside antenna 1.

When the tag antenna is sufficiently small, the magnetic flux going through the antenna 2 loop can be approximated as $B_{21} \cdot A_{loop}$, and their mutual inductance can be expressed as

$$M_{21} = \frac{B_{21} \cdot A_{loop}}{I_1} = (\frac{r^2}{r^2 + h_{21}^2})^{3/2} \cdot L_1 \quad (7)$$

Where $L_1 = \mu_0 \cdot A_{loop} / 2r$ is actually the inductance of antenna loop 1.

The coupling current inside antenna loop 2 induced from antenna 1 is

$$I_{21} = \frac{-I_1 j\omega M_{21}}{R_{chip} + 1/j\omega C + j\omega L} \quad (8)$$

Where R_{chip}, L, C are from the RLC equivalent model of the tag circuit.

D. Coupling Between Multiple Tags

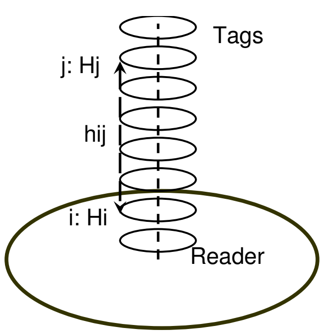

Figure 5. Coupling of multiple tag antennas in reader antenna NF

Considering multiple tag antennas stacked vertically with the separation h in between, as shown in Fig. 5. The distance from the lowest tag to the reader plane is H_0, hence the distance from the i^{th} tag to the reader plane is $H_i = (i-1) \cdot h + H_0$. The distance between i^{th} tag and j^{th} tag is $h_{ij} = (j-i) \cdot h$, the coupling current inside the i^{th} antenna, contributed from the current of the reader antenna, as well as the currents from all other tag antennas in the stack, can be formulated as

$$I_i = a_i I_0 - \sum_{j \neq i}^{n} b_{ij} I_j \quad (9)$$

where

$$a_i = \left(\frac{R^2}{R^2 + H_i^2} \right)^{3/2}, b_{ij} = \frac{-j\omega L \cdot r^3 / (r^2 + h_{ij}^2)^{3/2}}{R_{chip} + j\omega L + 1/j\omega C} \quad (10)$$

The above equation can be further expressed in the matrix form as

$$\begin{bmatrix} 1 & b_{12} & \cdots & b_{1n} \\ b_{21} & 1 & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} I_0 \quad (11)$$

Solving the matrix equation, we can derive the coupling current inside each of the stacked antennas as

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} 1 & b_{12} & \cdots & b_{1n} \\ b_{21} & 1 & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix}^{-1} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} I_0 \quad (12)$$

III. WEAK SPOTS PROFILE CALCULATION

Weak spots in the stack are those tags that, compared with other tags, need more power to be activated. To calculate the weak spots profile, we first define the *activation power (in dB)* to be the minimum transmission power level of the reader antenna that can activate the tag in the stack.

Using the equations introduced above, we can calculate the coupling current generated at each of the tag antenna loop in the stack at a certain reader transmission power level. We assume the sensitivity of the tags is -12dBm, and the tag impedance is 14-140j, which is the same as the tags used in later simulation and lab experiments. The -12dBm sensitivity is the minimum coupling power required in the antenna loop to

wake up the tag. Using the impedance of the tag equivalent circuit, we can then deduct the activation power required from the reader antenna.

Although all tag antenna rings can couple in the inductive field generated from the reader as well as other tags, we assume only one tag will respond to the reader's interrogation. This assumption complies with the UHF Gen2 anti-collision protocol.

Three activation power profiles of a stacked of 20 tags are calculated, where the separation between tags is set to be 2mm, 5mm and 15mm respectively. The profiles show an interesting distribution of the weak points.

Fig. 6 shows the activation power at 15mm separation. The x-axis denotes the tag position along the stack, where number 1 is closest to the reader antenna. The y-axis denotes the activation power of each tag. At this condition, it is not surprising to see that the activation power increases monotonically as the tags move further from the reader antenna. The weakest spot is at the far end of the stack because it receives the weakest coupling from the reader.

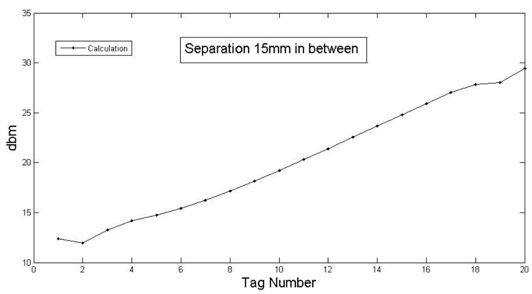

Figure 6. Activation power at 15mm separation

However, when we place the tags closer to each other, the profile begins to change. Fig. 7 shows the activation power at 5mm separation. The weakest spots, or the tags that need highest power to activate, are tag number 5 and tag number 16. These two tags are the ones located inside the two ends of the stack. The tags at the center and far-end of the stack are easier to be detected than these two weakest tags.

By studying again at the coupling matrix deducted earlier, this phenomenon can be explained qualitatively. Considering one tag coupled with the reader antenna, the coupling current inside the tag antenna is on the opposite direction of its driving current in the reader. For the convenience of the analysis, we call this coupling the *negative coupling*. However, the coupling current in one tag will again couple with other tags, the *secondary* coupling will generate currents that are in the same direction with the reader current, thus for other tags, their coupling effects with the reader are enhanced by the first tag, we call this *positive coupling*. When there are multiple tags in the field, the negative and positive coupling will all be accounted. Based on their relative locations to other tags and the reader, at some positions, the tag-reader coupling will be enhanced while at other positions, it will be reduced. The tag number 20 at the far-end of the stack still needs more activation power compared with the tag number 1, but it may not be the weakest spot because it receives less negative coupling from other tags.

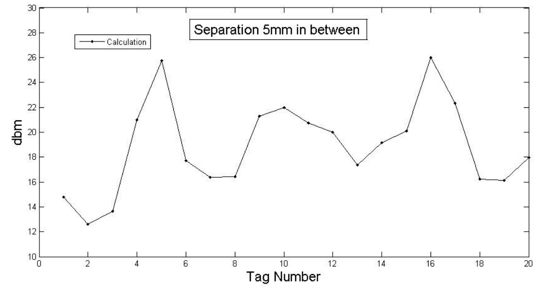

Figure 7. Activation power at 5mm separation

When the separation between tags is further reduced to 2mm, the negative and positive coupling are more obvious to demonstrate, as in Fig. 8. Compared with the profile of 5mm separation, the weakest spots are still inside the two ends of the stack, but they are moved inward further, to tag number 6 and number 15 respectively.

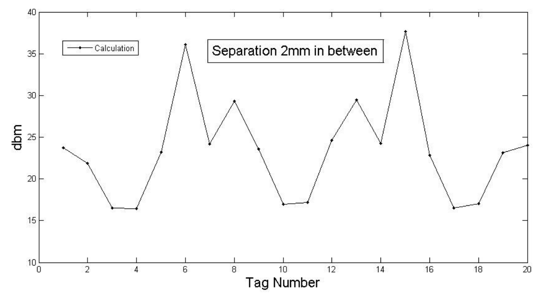

Figure 8. Activation power at 2mm separation

IV. EM TOOL SIMULATION

To further demonstrate the weak spots profile, we use AMDS, an antenna modeling and design system to simulate the activation power of the stacked tags. In order to compare the results with our lab experiments, the tags are modeled based on the exact geometry of Impinj® Disc® antenna, and the reader antenna is modeled based on the CSL-777 Brickyard® antenna, as shown in Fig.1 and Fig. 9. The tag inlay substrate is also modeled with the matched dielectric [17-19].

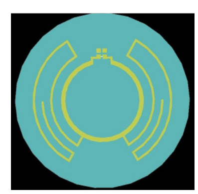

Figure 9. Tag antenna geometry in AMDS

The simulation results match well with our theoretical calculation, as shown in Fig. 10, Fig. 11 and Fig.12. We put

both the simulation and calculation results on the same figure to make it easier to compare.

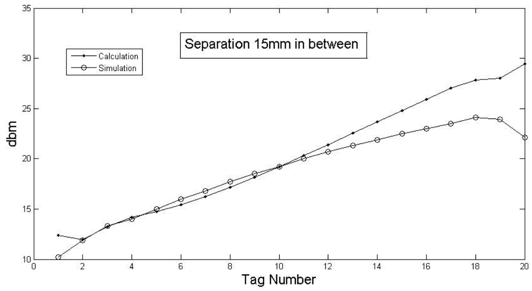

Figure 10. Activation power at 15mm separation (simulation and calculation)

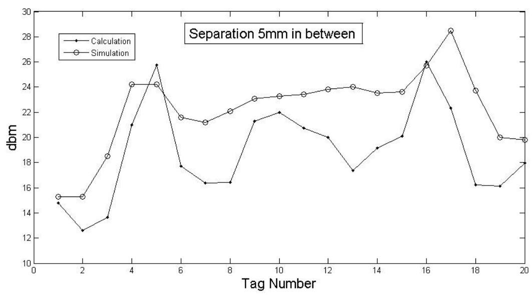

Figure 11. Activation power at 5mm separation (simulation and calculation)

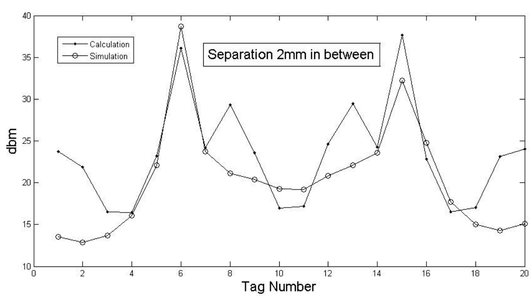

Figure 12. Activation power at 2mm separation (simulation and calculation)

V. EXPERIMENTS AND MEASUREMENTS

To further verify the results from calculation and simulation, we also test the activation power of a stack of 20 Gen2 tags with 15mm, 5mm and 2mm separation respectively. The tags and reader antenna and the experiment settings are the same as the ones we modeled in the EM simulation.

The experiments are conducted in the following steps. Each of the 20 tags is written with a pre-defined EPC code. Using a Gen2 reader, we SELECT the tag of interest and QUERY it to retrieve the EPC code. We gradually increase the reader transmission power level until the tag can be successfully selected and queried. We use this transmission power as the activation power of the tag of interest. We measure the activation power of all the 20 tags on the stack and the results are showed in Fig, 13, Fig. 14 and Fig.15 respectively, together with the results from theoretical calculation and EM tool simulation.

The measurement results show a very similar profile of the weak spots. At the separation of 15mm, the activation power increases as the tag moves further from the reader antenna. However, the reader we use in this experiment only allows the transmission power to be adjusted between 15dBm and 33dBm and cannot go beyond the range. For tag 1, 2, 3, 4, the activation power is actually below 15dBm, and for tag 17, 18, 19, 20, the activation power is actually more than 33dBm, we draw a flat line in the figure to show this limit. Nevertheless, we believe the monotonic profile will still hold beyond the range.

In the experiment with separation 5mm, the profile shows that the weak spots are moved inside the stack, and the two peaks of the profile are located at tag [5, 6] and tag [15, 16]. Although the profile does not match precisely with the calculation and simulation results (peaks at [4-5], [16-17]), we can still see that weak spots follow the similar distribution.

The testing results align much more nicely in the case of 2mm separation. The weakest spots are tag number 5 and 16 respectively, which are very close to the two weak spots at number 6 and 15 in our calculation and simulation results. It should be noticed that the profile from lab measurement is much smoother than that from calculation; the reason is probably that in real-life experiment setting, there are too many factors that can not be accounted in theoretical and simulation analysis.

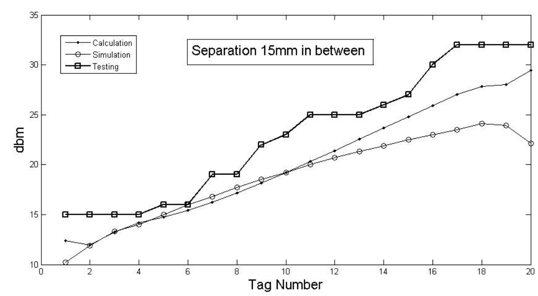

Figure 13. Activation power at 2mm separation (measurement, simulation and calculation)

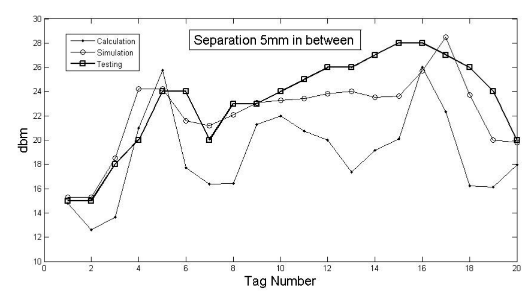

Figure 14. Activation power at 2mm separation (measurement, simulation and calculation)

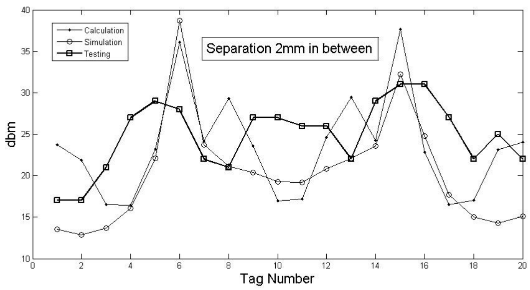

Figure 15. Activation power at 2mm separation (measurement, simulation and calculation)

VI. SUMMARY

In this paper, through the construction of mutual coupling models for antennas in near-field, the tag-tag and tag-reader antenna mutual coupling effects can be analytically formulated. Through our theoretical calculation, we demonstrated that the weak spots of stacked tags are mainly caused by the mutual inductive coupling between tags, and the profile of the weak spots is dependent on the separation between tags in the stack. Both EM tool simulation as well as field testing results also verified this analysis.

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